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HIGH STRAIN RATE PROPERTIES OF TANTALUM PROCESSED BY EQUAL CHANNEL ANGULAR PRESSING

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14. ABSTRACT
Current ingot refinement and solidification techniques used in tantalum processing often result in inconsistent mechanical properties. Subsequent processing by equal channel angular pressing (ECAP) has been shown to reduce or eliminate internal structural variations as well as part-to-part variability [2]. This paper presents the effects of ECAP processing on the properties of tantalum. The materials of interest are 2.5-inch round bar tantalum supplied by H.C. Starck and Cabot Supermetals. Three metallurgical conditions were examined for each material: as worked, fine-grain annealed, and large-grain annealed. Prior to annealing, each bar was processed eight times through a 135-degree ECAP die using route C and then forged into 0.25-inch thick plates. Mechanical property specimens were subsequently removed from the plates for low and high-rate uniaxial compression experiments. Orientation dependence was characterized by orienting specimen load axes through the thickness or in the plane of the forged plate. Wave propagation and anisotropy were studied using Taylor impact experiments.

15. SUBJECT TERMS
Tantalum, Taylor impact, ECAP, ECAE

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HIGH STRAIN-RATE PROPERTIES OF TANTALUM PROCESSED BY EQUAL CHANNEL ANGULAR PRESSING

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Abstract. Current ingot refinement and solidification techniques used in tantalum processing often result in inconsistent mechanical properties. Subsequent processing by equal channel angular pressing (ECAP) has been shown to reduce or eliminate internal structural variations as well as part-to-part variability [2]. This paper presents the effects of ECAP processing on the properties of tantalum. The materials of interest are 2.5-inch round bar tantalum supplied by H.C. Starck and Cabot Supermetals. Three metallurgical conditions were examined for each material: as worked, fine-grain annealed, and large-grain annealed. Prior to annealing, each bar was processed eight times through a 135-degree ECAP die using route C and then forged into 0.25-inch thick plates. Mechanical property specimens were subsequently removed from the plates for low and high-rate uniaxial compression experiments. Orientation dependence was characterized by orienting specimen load axes through the thickness or in the plane of the forged plate. Wave propagation and anisotropy were studied using Taylor impact experiments.

Keywords: Tantalum, Taylor impact, ECAP, ECAE
PACS: 62.20.-x, 62.20.Fe, 62.50.+p

INTRODUCTION

Developing forged plate tantalum with consistent mechanical and physical properties is an area of interest for high strain-rate applications. Mill practices for pure tantalum, specifically ingot refinement and solidification, often lead to inconsistent mechanical properties within the processed material. Evidence of the mill practices often continues through subsequent thermo-mechanical processing steps even with high levels of induced plastic work or recrystallization. This heterogeneity has been observed in upset forged tantalum plates where the processing history manifests in the form of texture banding [1]. Distinct regions of hard (111) and soft (100) crystallographic regions are encountered as one passes through the thickness of a forged plate (Figure 1). Research has shown that processing tantalum by equal channel angular pressing (ECAP) can reduce microstructural heterogeneities [2]. Thus it is of interest to examine the textural and microstructure modification by ECAP processing on tantalum plate material. The objectives of this research are to (1) process pure tantalum by ECAPing, forging, and annealing and (2) characterize the effects of the thermo-mechanical processing on the mechanical properties. The ultimate goal is to generate consistent structural properties of tantalum for high strain-rate applications.

Material

The materials of interest are commercially pure tantalum from HC Starck and Cabot Supermetals. All material was mechanically processed by ECAP eight passes using route C. The material was then forged into 0.25-inch thick plates. Three metallurgical conditions were investigated for each supplier's material: as worked (ECAP + forging only); annealed for 1 hour at 950°C (Cabot) or 1050°C (Starck) to produce an average grain diameter of 20 µm (fine grain); and annealed for 1 hour at 1250°C to produce an average grain diameter of 100 µm (large grain). Specimens were removed from the through-thickness (TT) and radial in-plane (IP) orientations of the forged plates, and annealing was performed within a vacuum furnace.

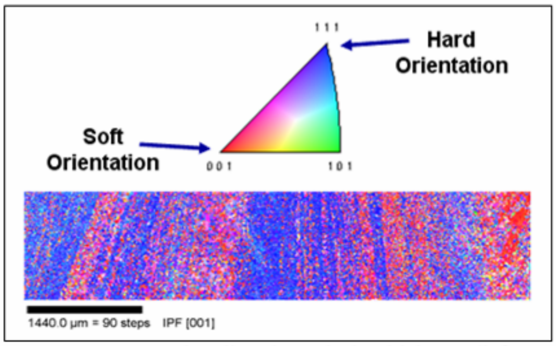

Figure 1. Texture banding through the thickness (left to right) of forged tantalum plate. [1]

Mechanical properties experiments

A series of quasi-static, split-Hopkinson pressure bar, and Taylor impact experiments as well as microhardness measurements were performed to characterize the materials in all three metallurgical conditions. The orientation dependencies of each metallurgical condition were analyzed relative to the IP and TT directions.

Taylor impact experiments were performed on specimens removed in the plane of the plates to characterize the dynamic material response. The Taylor impact experiment involves a right circular cylinder specimen (diameter = 5.33 mm, L/D = 10) launched into a rigid surface [3]. High-speed photography captures the dynamic deformation event while the impacted specimen can be recovered for postmortem analysis.

RESULTS AND DISCUSSION

An annealing study was performed to characterize the recrystallization behavior of the Cabot and Starck materials. Specimens were removed from the ECAPed and forged plates and annealed for one hour. Hardness measurements were made on the annealed samples, and the data is given in Figure 2. The hardness data indicates that the Cabot material recrystallizes at ~125°C lower temperature than the Starck material. Comparison of the data for samples oriented in the IP or TT direction revealed little orientation dependence, except in the as worked condition where the TT direction had higher values for both mills.

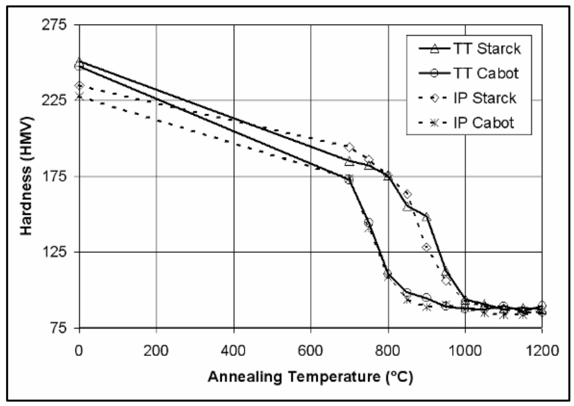

Figure 2. Vickers microhardness versus annealing temperature for ECAP and forged Cabot and Starck materials.

Low rate compression

Quasi-static compression experiments were performed at a strain rate of 0.01 s^{-1} for all three metallurgical conditions: as worked (AW), fine-grain anneal (FG), and large-grain anneal (LG). Data for specimens loaded in the IP direction are given in Figure 3 and for specimens loaded in the TT directions in Figure 4.

The mechanical properties at low rates show some level of orientation dependence, but no appreciable grain size effect. For both mills, the TT direction gave the highest yield strength values. In

the as worked condition, Cabot had slightly higher yield strength than Starck. It was noted that in the TT direction the as worked material still had some strain hardenability. While the hardening rates are linear, for the as worked TT direction, Starck had a slightly higher rate of hardening. In contrast, neither as worked material hardened in the IP direction. The as worked mechanical properties ranged from 800-900 MPa for the forged plate. Mechanical properties of these magnitudes have been attributed to tantalum wire with diameters of 1 mm or less [4].

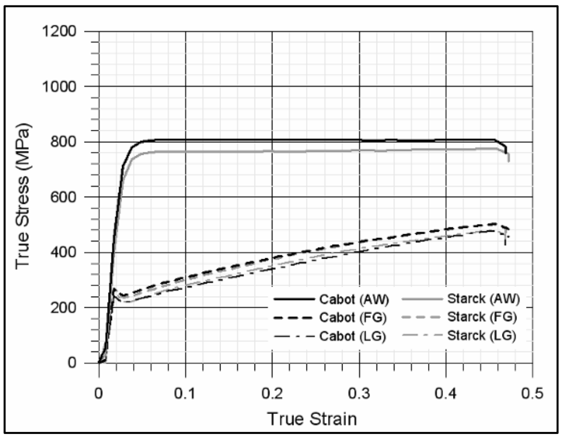

Figure 3. Low rate mechanical property data for Cabot and Starck (IP) specimens.

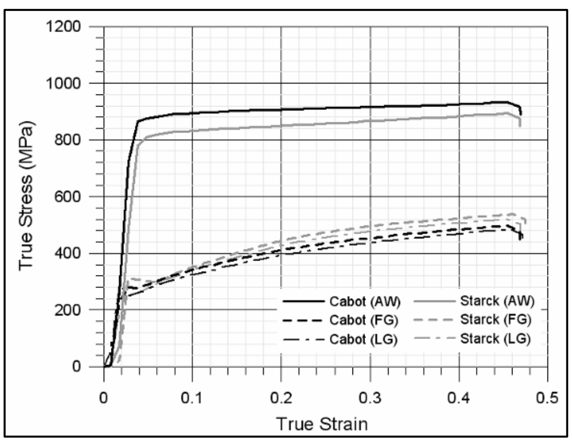

Figure 4. Low rate mechanical property data for Cabot and Starck (TT) specimens.

The annealed materials (fine and large grain) oriented in the IP direction exhibit linear hardening, and the data in Figure 3 shows little difference in mechanical properties between the two mills. For strains greater than 0.1, the stress levels are visually indistinguishable. In the TT direction, both materials have a slight non-linear hardening rate. Again, the Starck material has the higher hardening rate of the two.

High rate compression

High rate compression experiments were performed using a split-Hopkinson pressure bar (SHPB) with the results shown in Figures 5 and 6. Like the low rate experiments, the TT direction exhibits higher yield strengths than the IP direction. For the as worked condition in the IP direction, the stress level saturates at a true strain of 0.06. Above a true strain of 0.06, the stress decreases. In the TT direction, the as worked materials have 1 GPa yield strengths, with little subsequent ability to strain harden. Above a true strain of 0.1, the stress level decreases with increase strain.

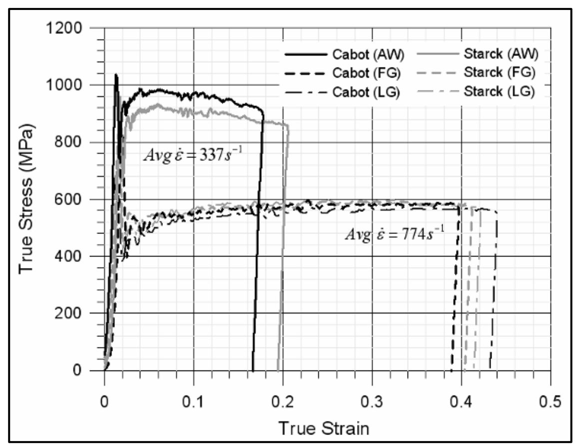

Figure 5. High rate mechanical property data for Cabot and Starck (IP) specimens.

The annealed materials in the IP direction have yield strengths at 440 MPa for both mills. These materials harden to a stress level of 580 MPa at a true strain of 0.25 to 0.35. In the TT direction, the annealed materials have average yield strengths of 560 MPa and harden to 610 MPa at a true strain of 0.1. Above a true strain 0.15, the stress decreases with increasing strain.

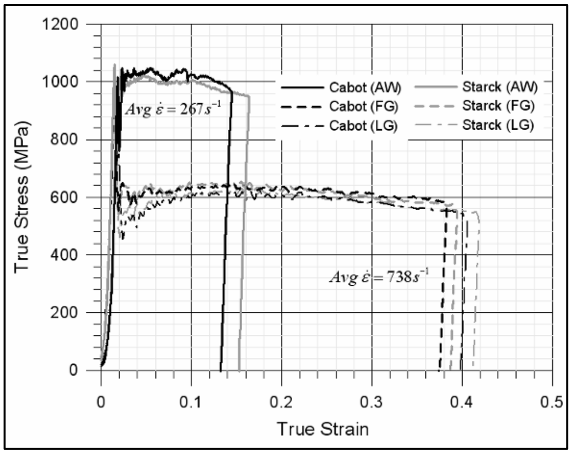

Figure 6. High rate mechanical property data for Cabot and Starck (TT) specimens.

Taylor impact

Taylor impact specimens were launched at an average impact velocity of 170 m/s. Analysis of the recovered specimen geometry showed strong mechanical anisotropy in the as worked and large grain materials, see Figure 7a. The extent of mechanical anisotropy was reduced in the fine grain material. In contrast, historical data for Cabot and Starck materials that had been forged and annealed (no ECAP) deformed in an isotropic manner (axisymmetric) upon impact, see Figure 7b. It should be noted that the current experiments (Figure 7a) are .21-caliber ECAP specimens with a length-to-diameter ratio of 10, and the historical experiments (Figure 7b) are .30-caliber forged specimens with a ratio of 5.

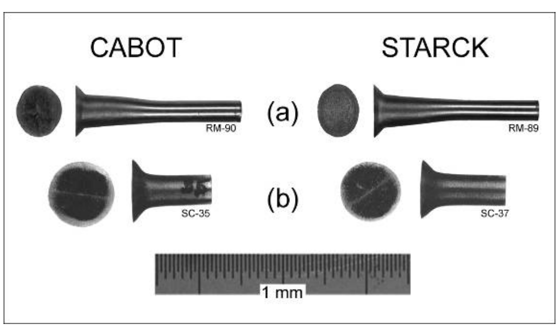

Figure 7. Profiles for recovered Taylor impact specimens processed by (a) ECAP and forging and (b) forging only. All specimens were annealed prior to testing.

CONCLUSIONS

Pure tantalum from Cabot Supermetals and H.C. Starck was processed by ECAP, followed by forging and annealing. Mechanical properties measured in the plane of the plate and through the thickness revealed an orientation dependence. In all cases, the through-thickness had higher yield strength values. Specimens recovered from Taylor impact experiments showed a distinct anisotropy to the deformation. This anisotropic response was most notable in the mushroom diameter which developed into an ellipse. Earlier work showed the deformation of forged and annealed material from the same suppliers to respond in an axisymmetric manner. The process of ECAP, forging, and annealing of tantalum from the two mills produced mechanical property data that was very consistent between the suppliers. The structures of the material that evolved through the thermo-mechanical processing generated a strong orientation dependence relative to the in-plane and through-thickness directions.

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High Strain Rate Properties of Tantalum Processed by Equal Channel Angular Pressing

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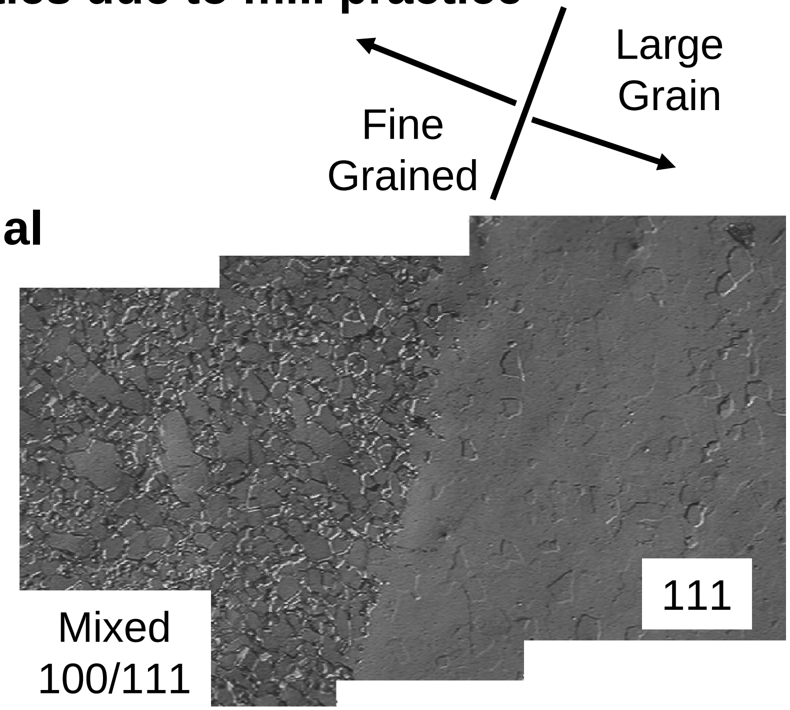
O'Brien & Associates
Metallurgical Consultants

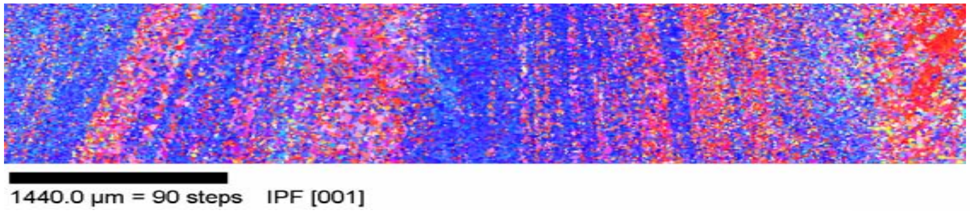
Outline

- Material
- Objectives
- Physical Properties
  - Optical microscopy
  - X-ray diffraction*
- Mechanical Properties
  - Quasi-static
  - High-rate (split Hopkinson pressure bar)
  - Taylor impact
- Conclusions

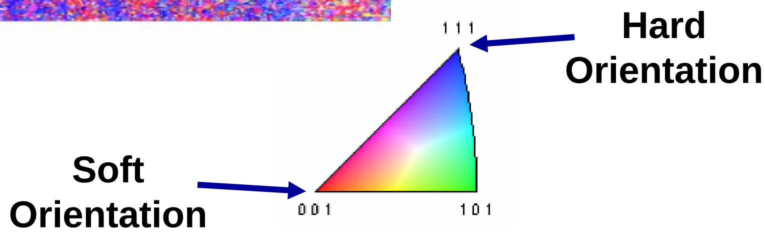
Material

- **Pure tantalum concerns**
  - **Lack of consistent mechanical properties due to mill practice**
    - **Ingot refinement**
    - **Solidification**
  - **Texture banding in forged plate material**
  - **Microstructural heterogeneities**
- **US suppliers**
  - **Cabot Supermetals**
  - **H.C. Starck**





Source: John Bingert, LANL



Objectives

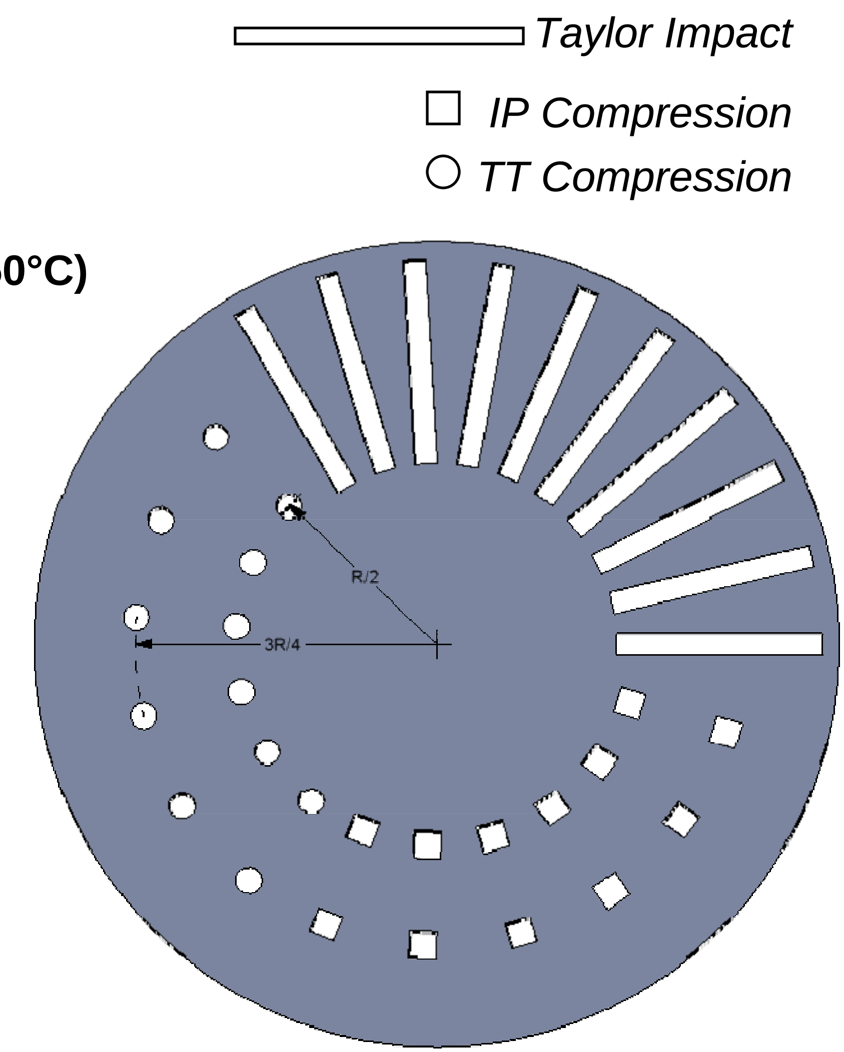
- **Objectives**
  - ECAP tantalum 8 passes route C
  - Forge material into 0.25”-thick plates
  - Characterize the effects of ECAP, forging, and annealing on mechanical properties

- **Long-term goal**
  - Generate consistent structural properties for high strain rate applications
- **Relevant studies**
  - Microstructural homogenization through equal channel angular pressing (ECAP) [1]
  - Uniform texture [2]
  - High rate properties of tantalum [3]

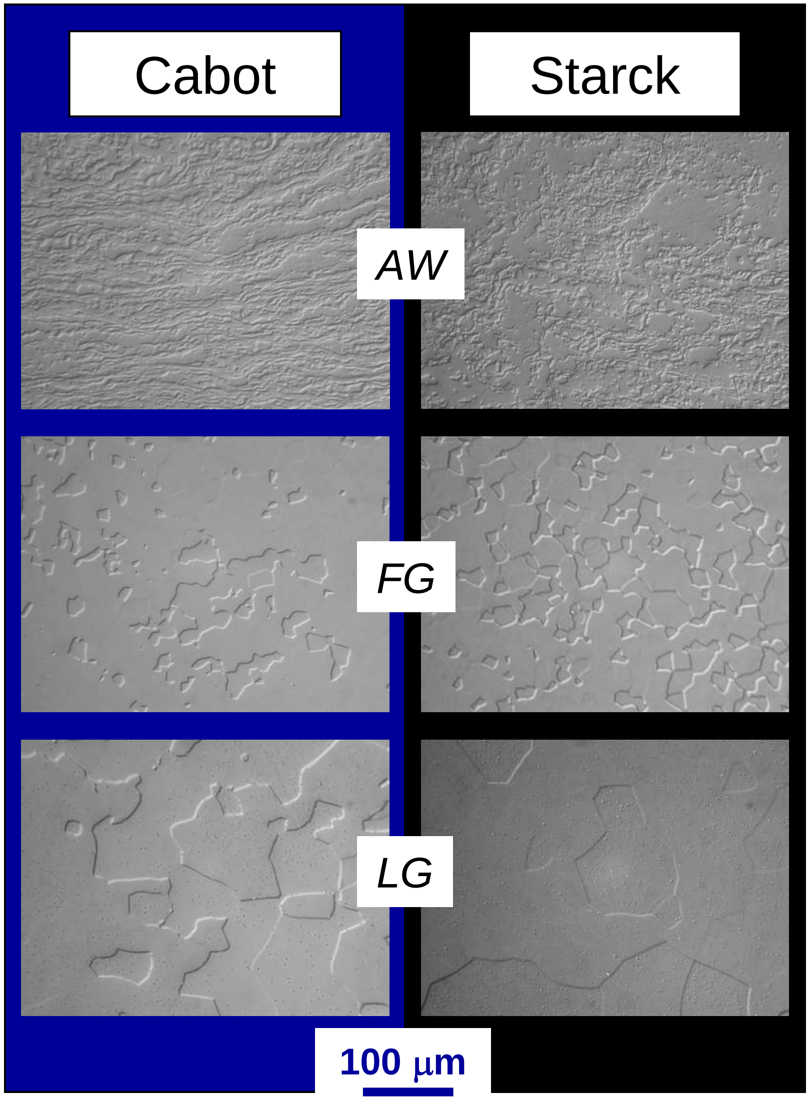
[1] Mathaudhu & Hartwig, MSE A 426, 2006
[2] House et al, ICOTOM, 2002
[3] Chen, Gray, & Bingert, TMS, 1996

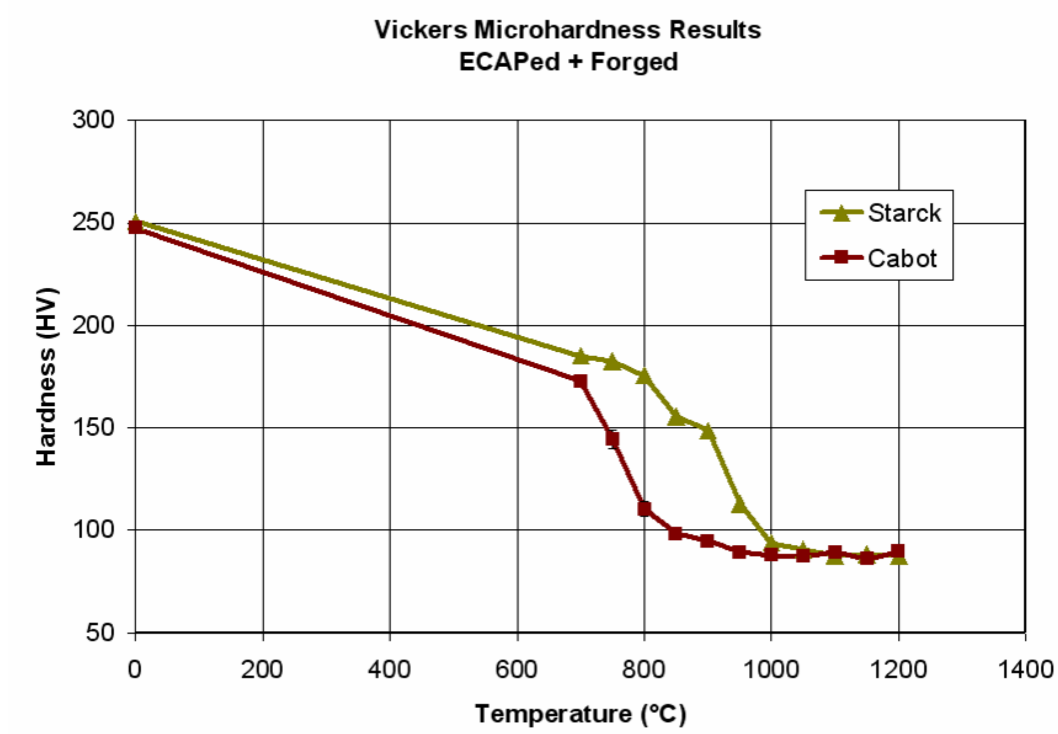
Material Characterization

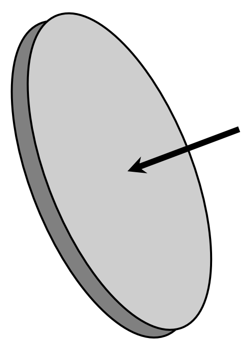
- **Baseline material**
  - **ECAP + Forge**
    - **As worked**
    - **Fine grain (Cabot-950°C; Starck-1050°C)**
    - **Large grain (1250°C)**
- **Mechanical property experiments**
  - **Compression**
    - **In-plane & through-thickness**
      - **Quasi-static**
      - **High rate**
  - **Taylor impact**
    - **In-Plane**



Annealing Study
Through thickness



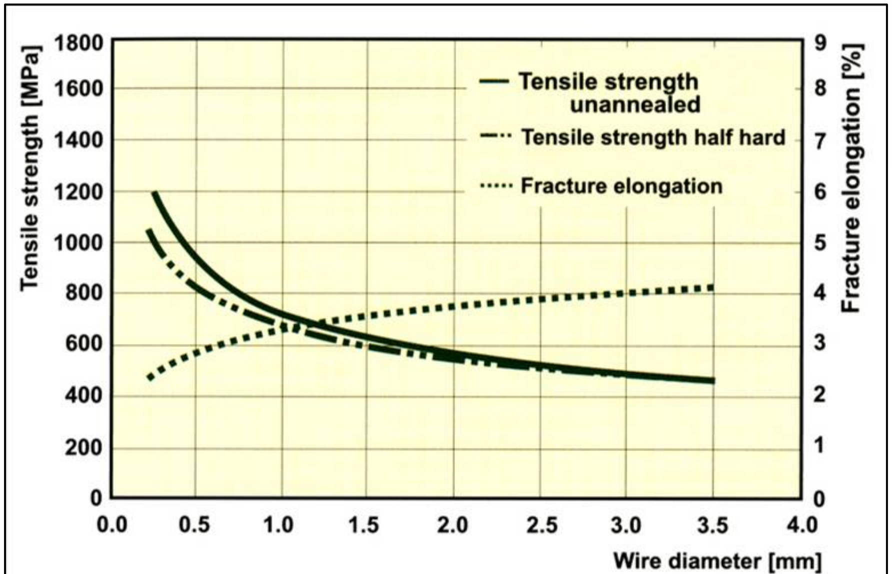




Measurement direction

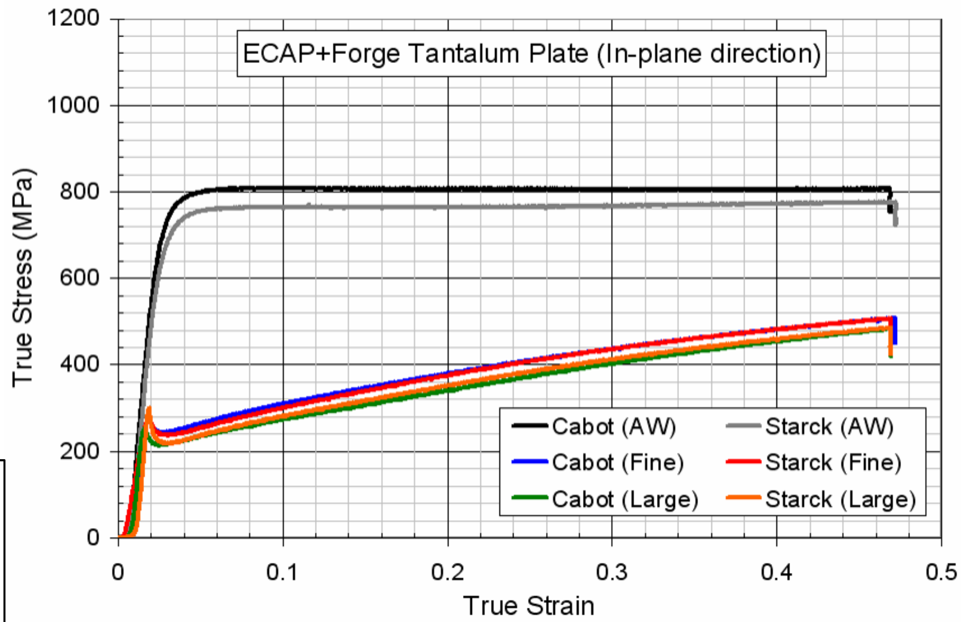
Mechanical Properties
Quasi-Static ($0.01\ s^{-1}$)

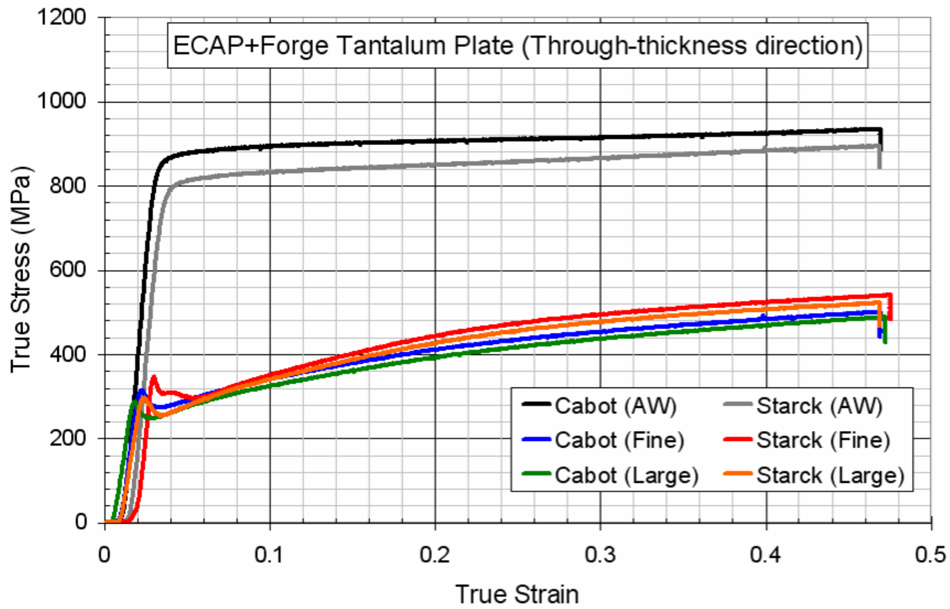
- **Through thickness**
  - **Higher yield strength**
  - **Limited hardening**
- **In plane**
  - **No hardening**



*Typical tensile strength and elongation at fracture values at room temperature for **unannealed** TaS and TaM wires*

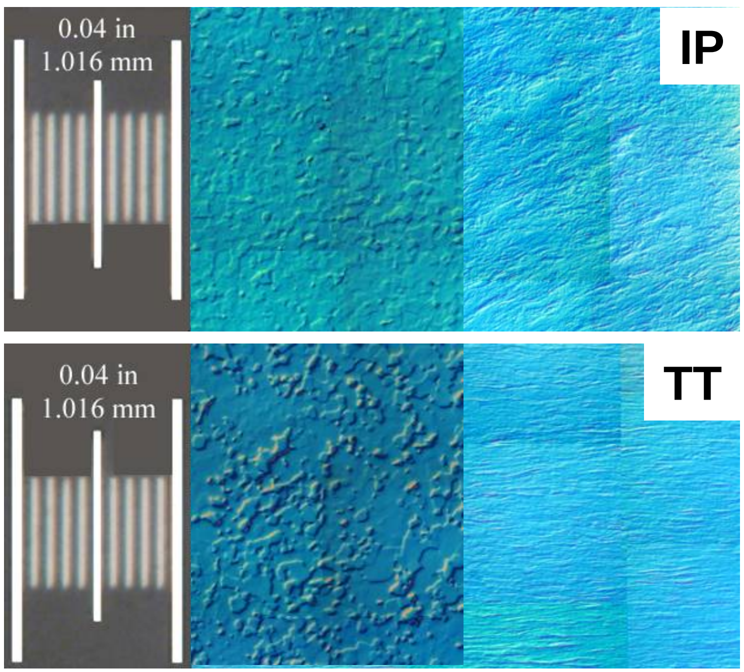
Source: Plansee

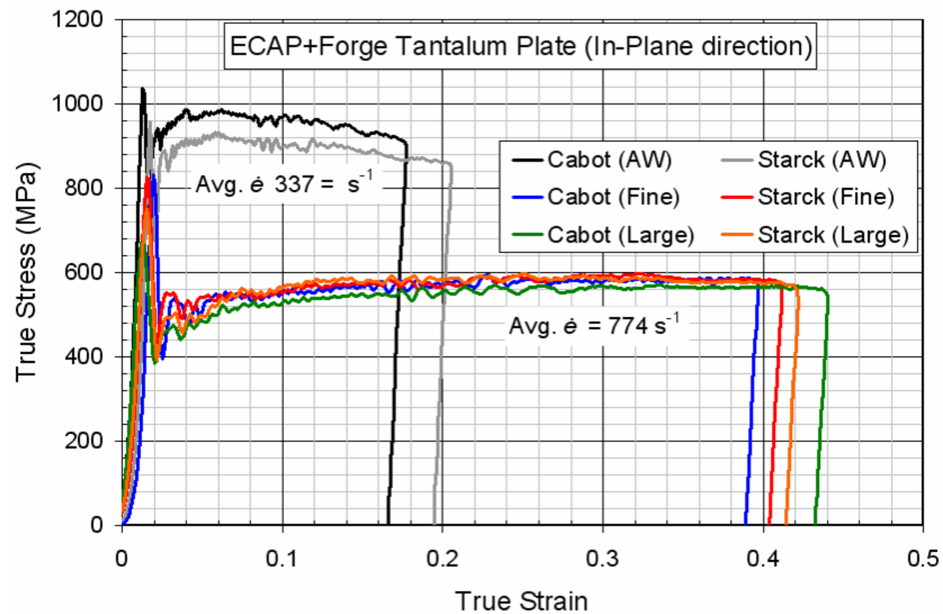


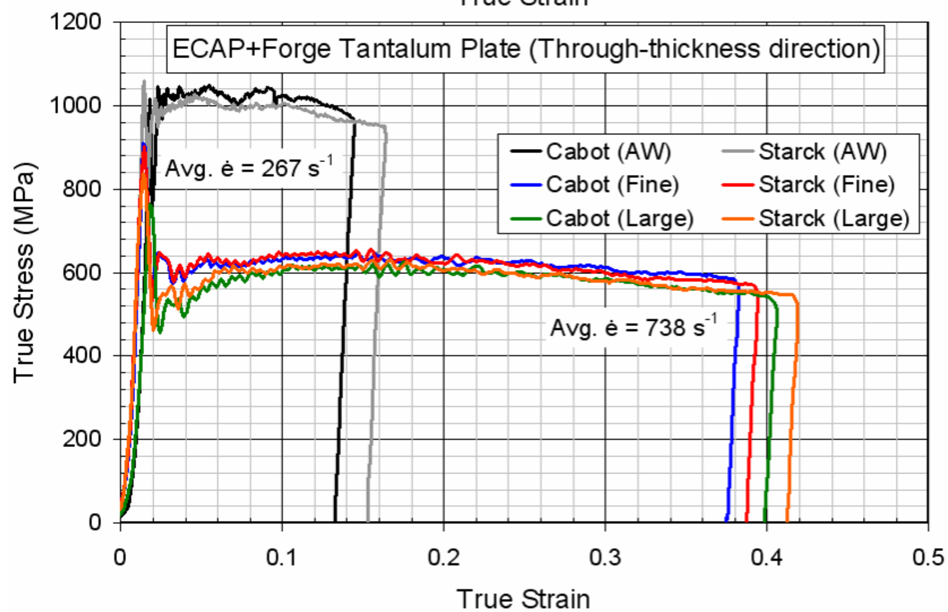


Mechanical Properties
Split-Hopkinson Pressure Bar

- **Through thickness**
  - **Higher yield strength**
- **Limited thermal sensitivity**
- **Adiabatic condition**
  - **Consistent response between orientations**

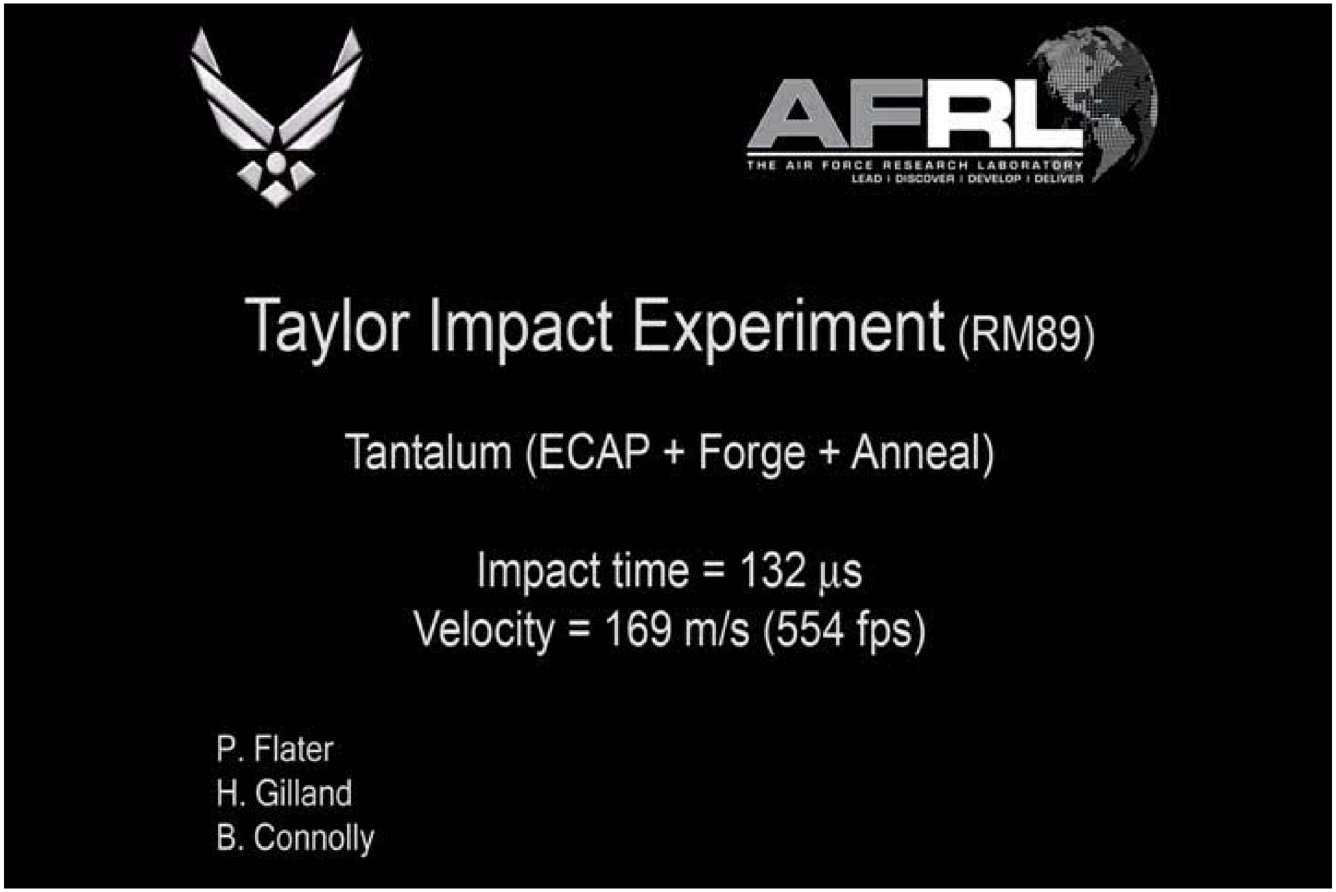




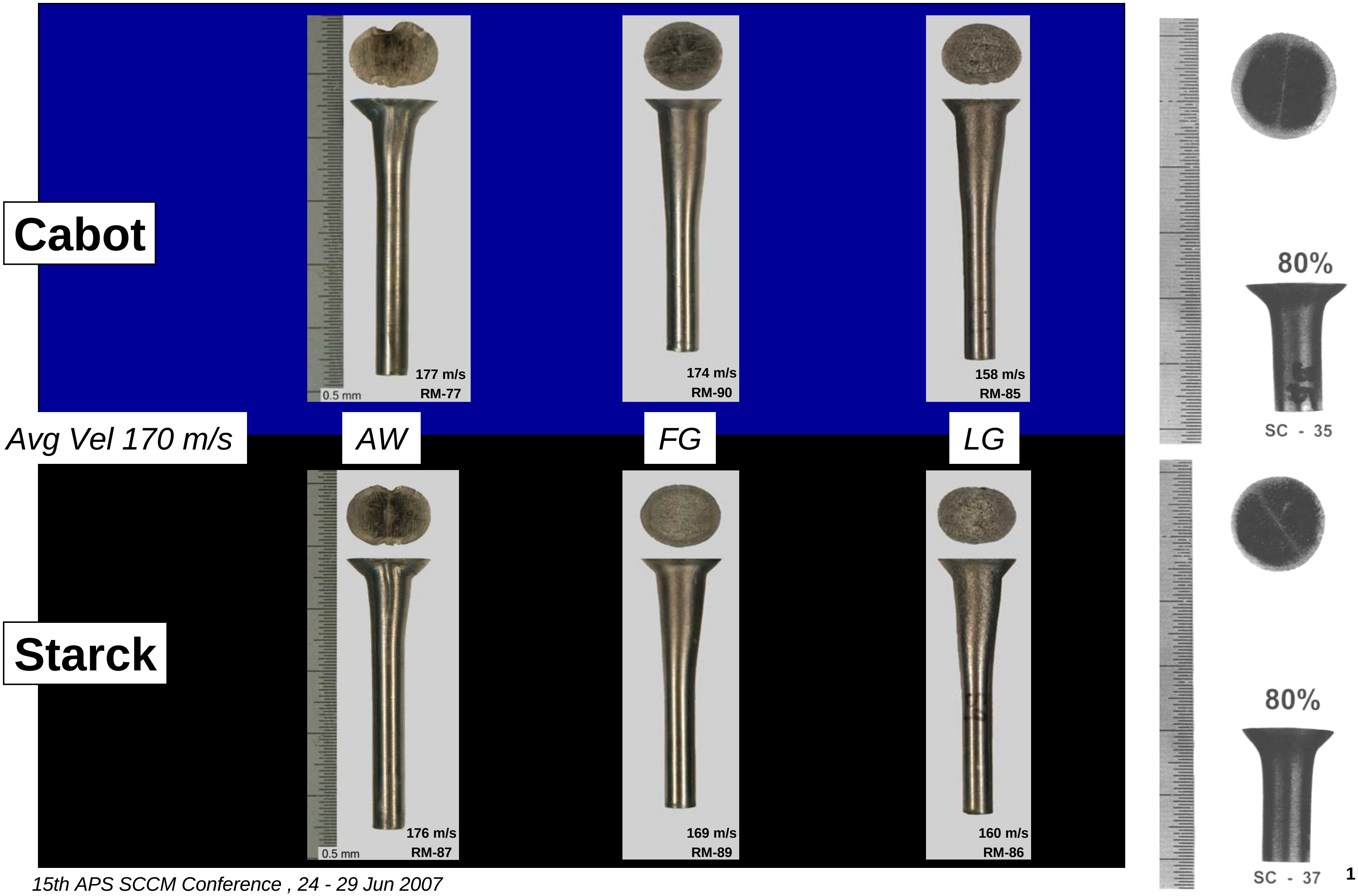


Impact Experiments

- **Taylor impact experiment (G.I. Taylor, 1948)**
  - **High-rate compression test**
  - **Compare profile of ECAP + forge material to forge only material**



Impact Experiments



Conclusions

- **Mechanical property measurements were consistent between Cabot & Starck processed via ECAP**
- **Yield strength:**
  - **Quasi-static ~850 MPa**
  - **High rate ~1000 MPa**
  - **Good agreement with the Plansee data for fine-diameter Ta wire**
- **ECAP eliminated grain structure variations in plate material**
- **Subtle differences between IP & TT orientations**
- **Strong anisotropic material response in Taylor impact testing does not appear to be consistent with the limited orientation dependence found in the SHPB experiments**
- **FUTURE STUDIES – Detailed texture analysis of materials to characterize the extent of banding and texture evolution**